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GALILEO: CHALLENGES ENROUTE TO JUPITER

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The Galileo spacecraft is now on its three-year direct Earth-to-Jupiter transfer trajectory. Jupiter arrival (Probe entry) is scheduled for 2:05 pm EST, December 7, 1995. The Galileo Probe will be the first human-made object to enter the atmosphere of an outer planet, while the Orbiter will be the first artificial satellite of an outer planet. A two-year Jupiter orbital mission is planned.

Following launch on October 18, 1989, Galileo spent just over three years executing its Venus-Earth-Earth Gravity Assist (VEEGA) mission phase to achieve the heliocentric energy necessary to reach Jupiter. Midway through its Earth-to-Earth leg, on October 29, 1991, Galileo became the first spacecraft to encounter an asteroid. Six months earlier in April 1991, the spacecraft's high-gain antenna (HGA) failed to deploy properly. The special guidance, navigation, and control (GN&C) problems associated with a 20-month campaign of maneuvers to free the stuck antenna and successfully perform the asteroid encounter without it are described. The overall mission and spacecraft status are also reported.

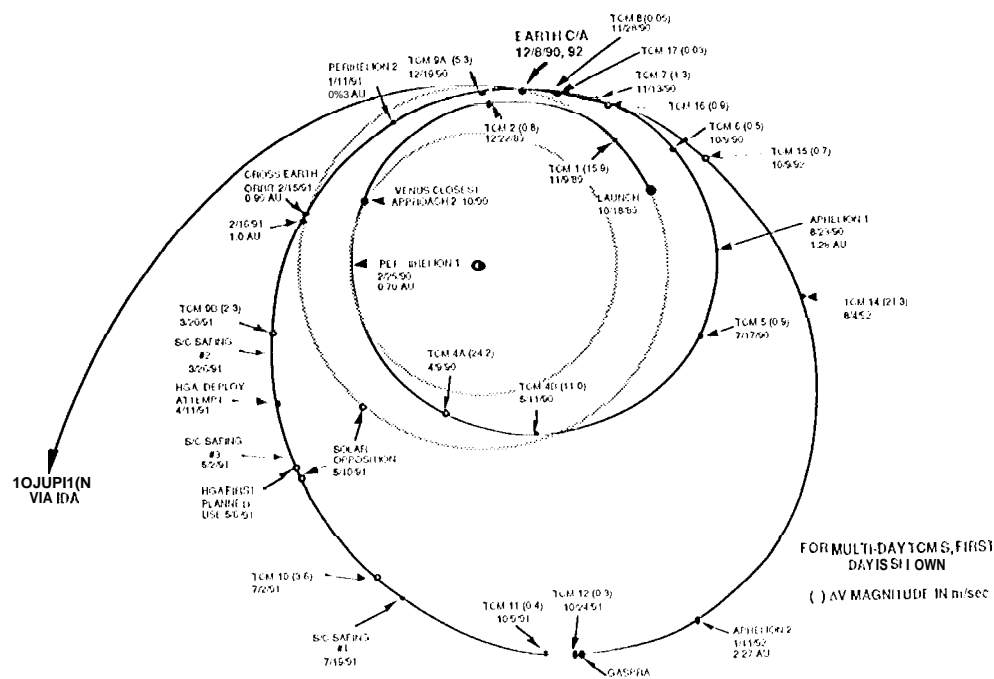
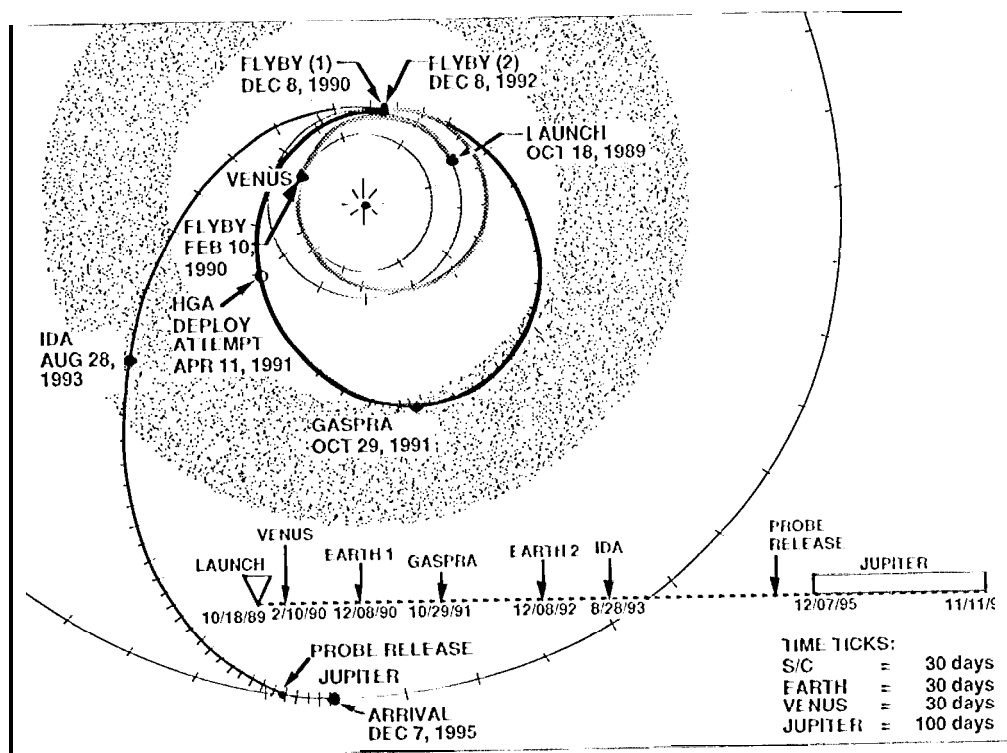
INTRODUCTION

Galileo is now well into its fourth year of interplanetary flight. The Galileo spacecraft is performing beautifully, except for its high-gain antenna (HGA), which remains stuck in a currently useless, partially deployed configuration. The Project is now preparing to do the mission on the low-gain antenna (LGA) which has been used for virtually all communication since launch (an aft-facing second LGA was used occasionally). At least 70 percent of the scientific objectives can be achieved with the LGA including 100 percent of the Atmospheric Entry Probe Mission and several thousand images including the highest resolution images of the Galilean satellites ever planned (Ref. 1). Some of the GN&C challenges experienced to date are the subject of this paper. See References 2 & 3 for a comprehensive description of the Galileo mission, its instruments, and investigations.

THE VEEGA TRAJECTORY

The VEEGA (Venus-Earth-Earth-Gravity-Assist) trajectory was the only way to get the 2.7-metric-ton Galileo spacecraft to Jupiter with the Shuttle/Inertial Upper Stage (STS/IUS)

launch vehicle. As seen in Fig. 1, the second Earth gravity assist (EGA2), 011 December 8, 1992, placed Galileo on a three year "direct" trajectory to Jupiter. The entire VEGA trajectory from launch on October 18, 1989 through EGA2 was flawless. Fig. 2 shows the



location and magnitude of each propulsive maneuver (also known as trajectory correction maneuver or TCM). Note that due to excellent navigation performance TCM3 and 'J'h'113 were not needed. Fig. 3 presents the Earth2 delivery accuracy. The delivery error of less than 1 km allowed cancellation of TCM18, the first post-Earth2 propulsive maneuver. A key factor in the Earth2 delivery accuracy was the relatively new data type called AI OR (delta Differenced One-way Range) wherein the Deep Space Network (DSN) compares the difference in the time of receipt at two of its complexes of a quasar signal with the difference for the spacecraft signal, and through triangulation precisely determines the angle between the spacecraft and the known quasar direction. Thus, in addition to the long-standing high-precision measures of Doppler and range, we now have direction as well for use in the orbit determination process. The Goldstone, California complex is used with the Madrid, Spain complex for an "east-west" measurement and with Canberra, Australia for a "north-south" measurement.

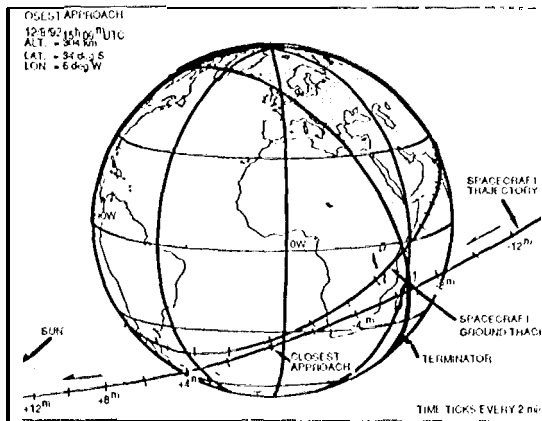


Fig. 3a Ground Track of Earth 2 Flyby

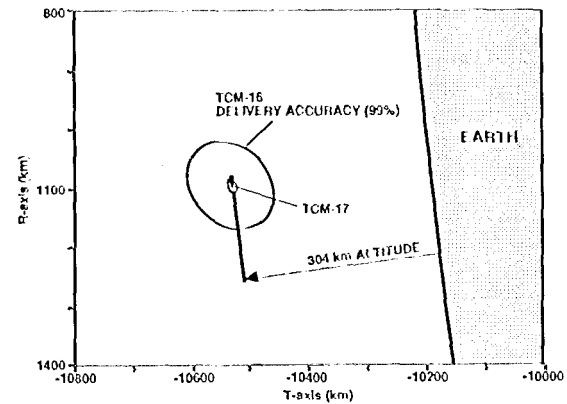


Fig. 3b Galileo Navigation Accuracy

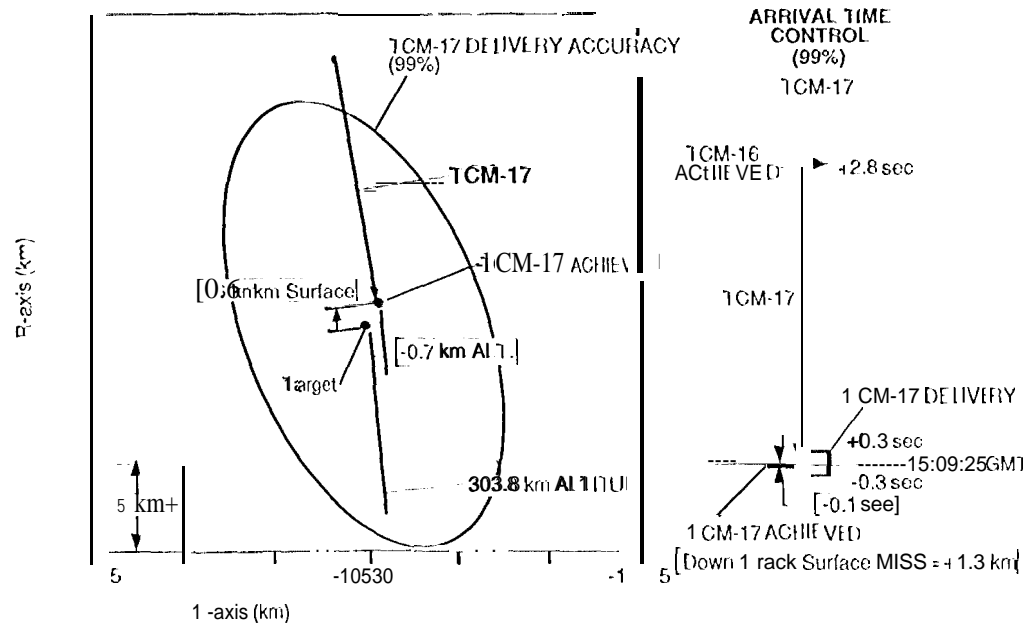


Fig. 3c Galileo Navigation Accuracy - Detail

GASpra ENCOUNTER

On October 29, 1991, Galileo became the first spacecraft to visit an asteroid. Galileo flew past the asteroid Gaspra at a relative speed of 8 km/s. At closest approach Galileo was only 1.5 sec early, 11 km from the aim point, and only 2 km from the planned flyby distance of 1600 km.

The first Earth-Gravity-Assist (EGA1) on 1 December 8, 1990 (Fig. 1), not only "pumped up" Galileo's heliocentric orbit from a period of about one year to a period of exactly two years, but also "cranked" the orbit through an inclination change to achieve the 4.5-deg ecliptic inclination required to reach Gaspra. Thus, EGA1 produced the Gaspra encounter. Fig. 2 shows the locations and magnitudes of the Gaspra approach propulsive maneuvers.

The greatest GN&C challenge of an asteroid encounter arises from the large uncertainty in the ground-based asteroid ephemeris. Direct spacecraft observations of the target are required to design the final propulsive maneuvers and instrument pointing. Originally, it was planned to transmit about forty optical navigation pictures judiciously scheduled over the last month of approach. Each picture would be transmitted to Earth in realtime in just one minute over the HGA. (Note that the optical navigation processing is done on the ground at JPL; there is no autonomous onboard spacecraft navigation capability.) Because the HGA was not usable due to its deployment anomaly, a Gaspra optical navigation picture could only be obtained by first recording it on the tape recorder and then sequentially reading -160 lines (each picture has 800 lines) at a time into the central computer memory. Those lines were then read out of memory and transmitted to Earth via the 40 bps engineering channel—the highest rate possible at the nearly 3 a.u. spacecraft-to-Earth distance over the low-gain antenna (LGA) into one of the DSN 70-10 ground antennas. Thus, it took about 80 hours to obtain one picture (vs. one minute over the HGA). Due to the overall complexity of this process and limited 70-m tracking time, the Gaspra navigation strategy had to be redesigned for only four pictures. However, this drastic reduction in the number of "opnav" pictures was largely mitigated by incrementally slewing the camera platform with the shutter open to obtain typically five data points (instead of one) per picture.

In order to capture high resolution images of Gaspra, spatial mosaicking was required, as illustrated in Fig. 4, to cover the final approach navigation uncertainties. Also, elaborate operations plans were designed and tested to adjust the pointing of each mosaic 10 hrs before encounter based on the final opnav picture shuttered 8 days before encounter. In actuality, the trajectory control was so good using the first three opnav pictures that the late pointing adjustment was not required. At the adjustment decision point the knowledge accuracy was three times better than expected. Consequently, it was then virtually certain that Gaspra would be in the center frame of the earlier mosaic. During planning for the Gaspra encounter for the LGA it had been determined, based on the forecast navigation accuracy, that many frames of a mosaic would have to be played back to have a reasonable chance of getting the one with Gaspra in it. Accordingly, the plan was to wait until Earth 2 approach over a year later to return all the frames at the high data rate. However, now that it was "known" Gaspra was in the center frame, 80 hrs of additional 70-10 DSN tracking was negotiated to return the first-ever image of an asteroid the second week after the encounter. In fact, through clever manipulations, the operations engineers found the image in the center of the center frame and played back the center one-fourth of each of the four different filter center frames to obtain the first and highest resolution color image. Similarly, the highest resolution (black and white) image was obtained by playing back parts of two frames of the final, 51-frame (single-filter) mosaic when the 40-bps rate became available in May 1992. The

Gaspra encounter was Galileo's most important "interplanetary science of opportunity" objective. It was a grand success. References 1, 4, 5, 6, and 7 give more details.

THE HGA DEPLOYMENT ANOMALY

The HGA was commanded to deploy on April 11, 1991. It is basically a Tracking and Data Relay Satellite (TDPRS) antenna. The reflector consists of 18 graphite epoxy ribs supporting a flexible gold-plated molybdenum wire mesh in a 4.8-in -dia, parabolic-shaped dish. As seen in Fig. 5, the antenna is analogous to an inverted umbrella. Due to shuttle launch loads and the shuttle's payload bay envelope, the ribs and mesh are "closed" against the central tower for launch. Each rib was "tied" to the tower with a spoke tensioned to 85 lbs (Fig. 6); the rib is supported by a pair of "locating" pins inserted into receptacles on the tower straddling its spoke. Immediately after launch the Central Release Mechanism was fired to release the 18 spokes. The deployment mechanism is a pair of electric motors which turn a ballscrew, causing the ballnut to raise its attached carrier ring. This action causes each of 8 pushrods, which conned the ribs to the ring, to push its rib out around the rib hinge point 68 deg, in order to seat the rib on its stop. In a normal deployment the ribs unfurl symmetrically like the petals of a flower in about three minutes. When commanded, the motors drew excessive current and stalled in just under one minute. The spacecraft-sequenced shutoff backup cut off the motors at eight minutes. The HGA deployment anomaly diagnosis and recovery attempts have required a tremendous effort over the past two years, including many totally unanticipated GN&C activities.

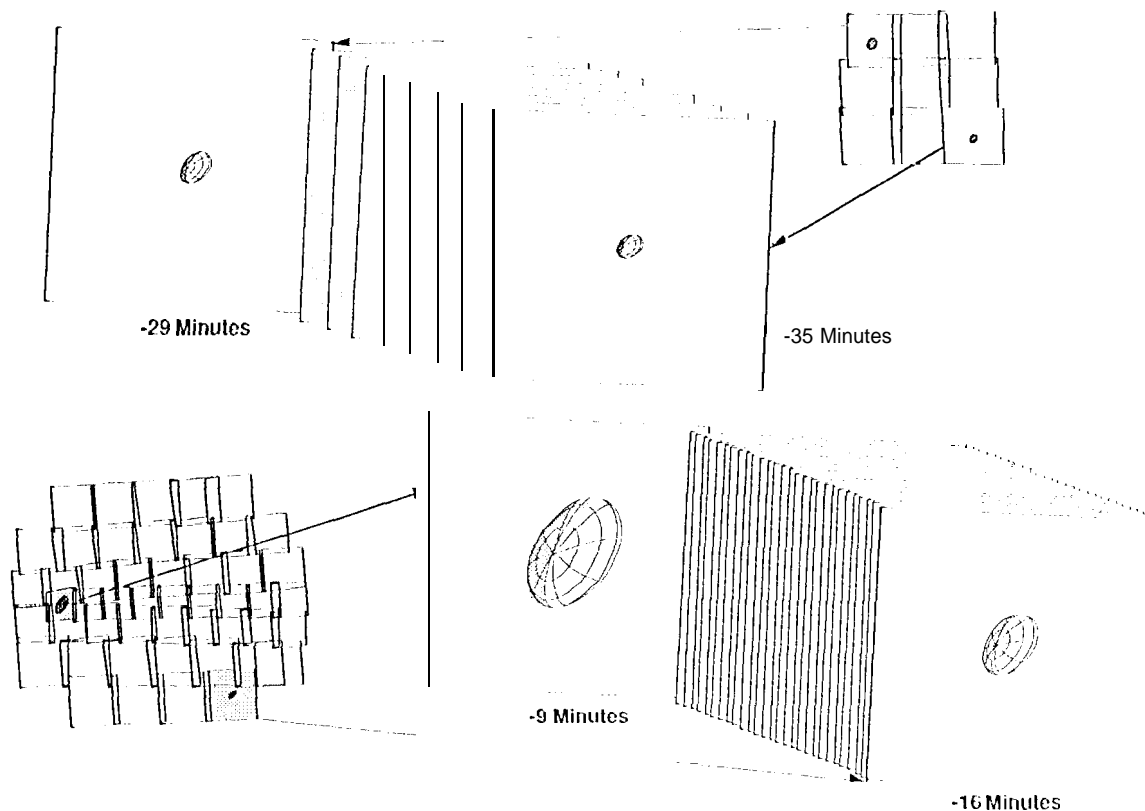


Fig. 4 Gaspra Observations from -35 to -9 min

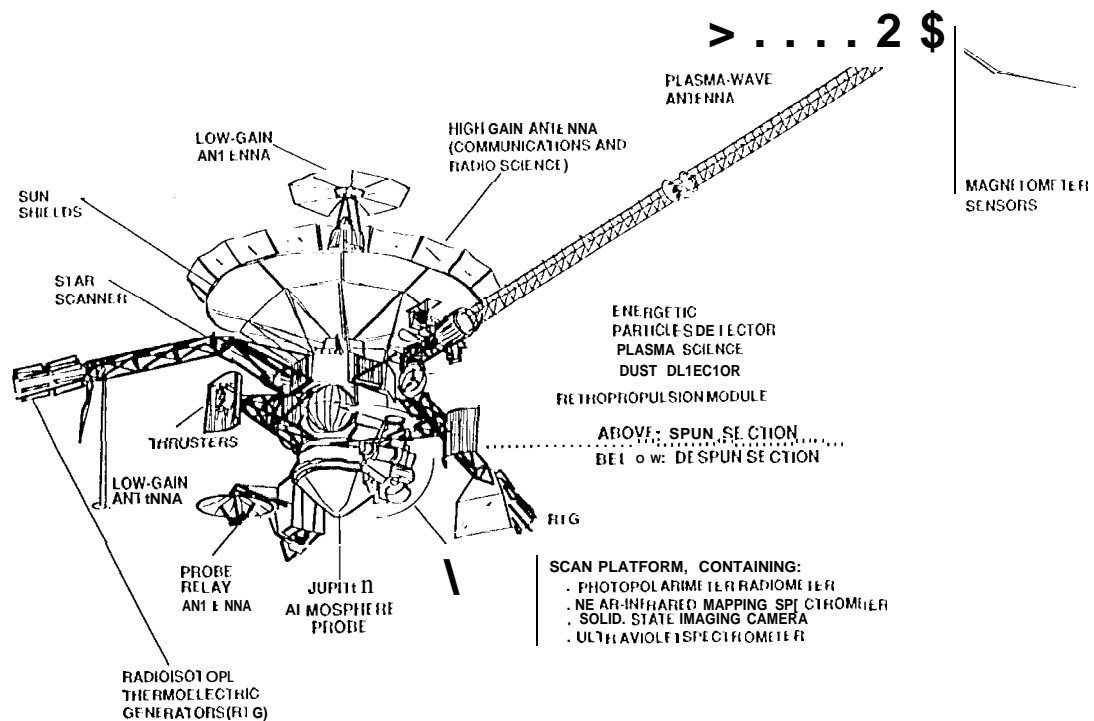


Fig. 5a Galileo Spacecraft Configuration

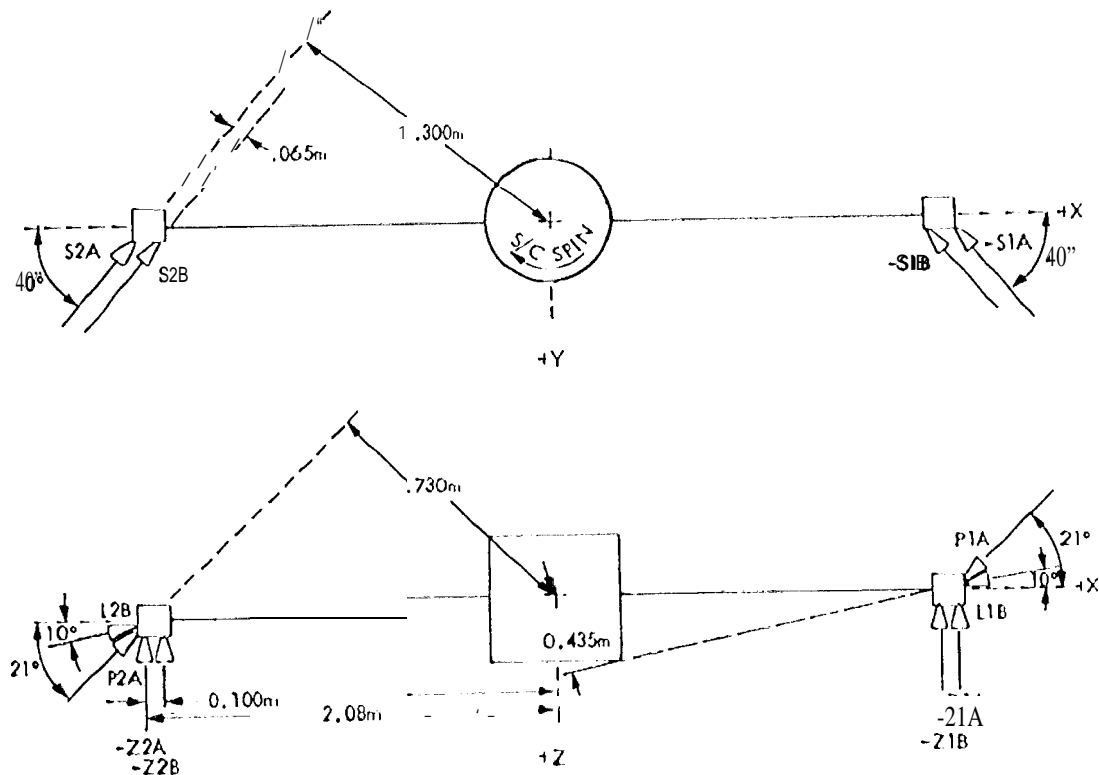


Fig. 5b 10-N Thrusters Configuration

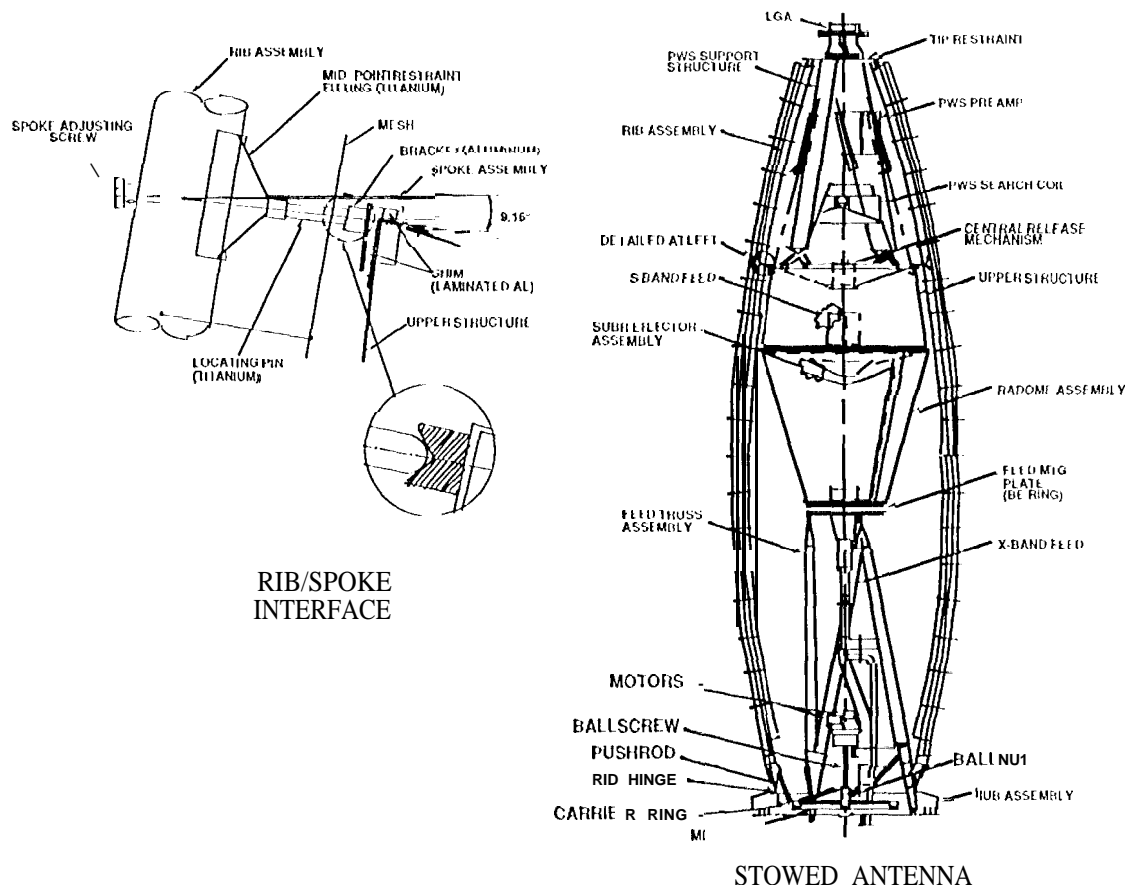


Fig. 6 JIGA Configuration

In the first hours after the anomaly, what had occurred was a great mystery. The most compelling evidence that at least some deployment had occurred came serendipitously from the sun gate sensor. The sun gate was added to Galileo when the JIGA trajectory was selected, which meant that a spacecraft designed to operate at solar distances from 1 to 5 a.u. now also had to survive at 0.7 a.u., i.e., at Venus. If the spacecraft suffered an attitude anomaly such that the sun moved more than a few (preset) degrees off the centerline, the sun gate would autonomously trigger a sun acquisition. This action would ensure that the sunshades would always protect critical elements of the spacecraft. No such attitude anomaly ever occurred, but the sun gate has been invaluable in diagnosing the JIGA anomaly.

It was noticed that the sun gate signal changed at the deployment event. Deep nulls were occurring at the spacecraft spin frequency. Clearly, some part of the JIGA was now partially obscuring the sun gate. Another attitude control feature, the onboard spin-rate estimate (SRE), had dropped (from 2.89 rpm) by only 0.3 mrad/s - one-fourth the drop predicted for a nominal deployment - indicating a partial deployment. The realtime telemetry of the SRE showed a gradual drop throughout the eight-minute motors-on time. This suggested that deployment continued throughout the eight minutes, leading some people to speculate that the JIGA was near full deployment and needed just another turn-on. However, the SRE is filtered and subsequent data analysis showed that the spin-rate change occurred within the first minute, consistent with the telemetered deployment motors current reaching stall value.

Fig. 7 illustrates the sun gate obscuration. Typically, the spacecraft spin axis (well within a degree of the spacecraft centerline) is a few degrees off the sunline. The sun gate is boresighted with the centerline (z-axis). During each spin period, the sunline traces out the conical surface shown. During its deployment, Rib #2 "slices" through this cone. The deployment angle of Rib #2 determines the spacecraft off-sun angle where obscuration begins. Thus, the Rib #2 deployment angle was determined to be 35 deg by finding the sun angle for the onset of sun gate obscuration.

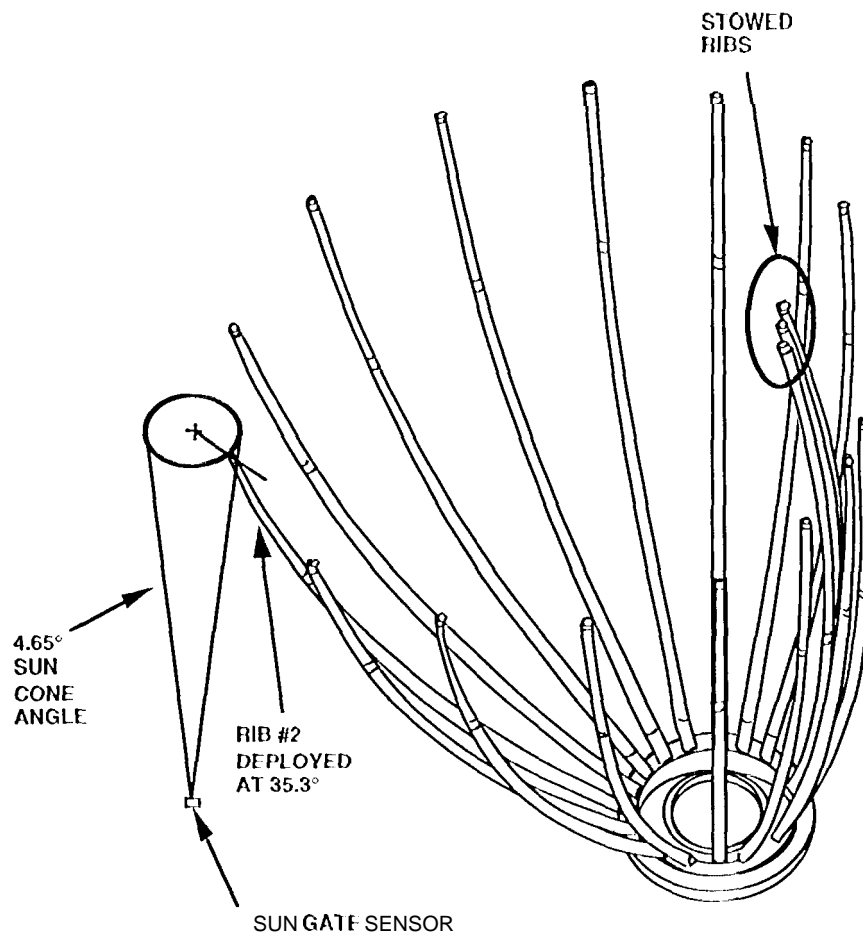


Fig. 7 Sun Gate Observation by Rib #2

Galileo is a dual-spin spacecraft (Fig. 5). It spins about the principal axis-of-inertia, which is nearly coincident with the centerline z-axis. This axis is called the "wobble-axis" since the spacecraft wobbles around it. As mass properties change (e. g., propellant expenditure, probe release, etc.) the wobble axis moves in the spacecraft frame. The angles of the RTG booms to the centerline are periodically adjusted by ground command to realign the wobble axis with the centerline. In a process called wobble compensation, data from the star-scanner-based celestial-attitude reference system in the attitude control computer and the gyros on the despun scan platform are used in ground-based software to determine the wobble axis orientation in the spacecraft frame and to then determine the RTG-boom-angle adjustments required to realign the wobble axis. Fig. 8 shows the shift in the wobble axis during the deployment attempt, which clearly indicated an asymmetric deployment in the direction of Rib #2.

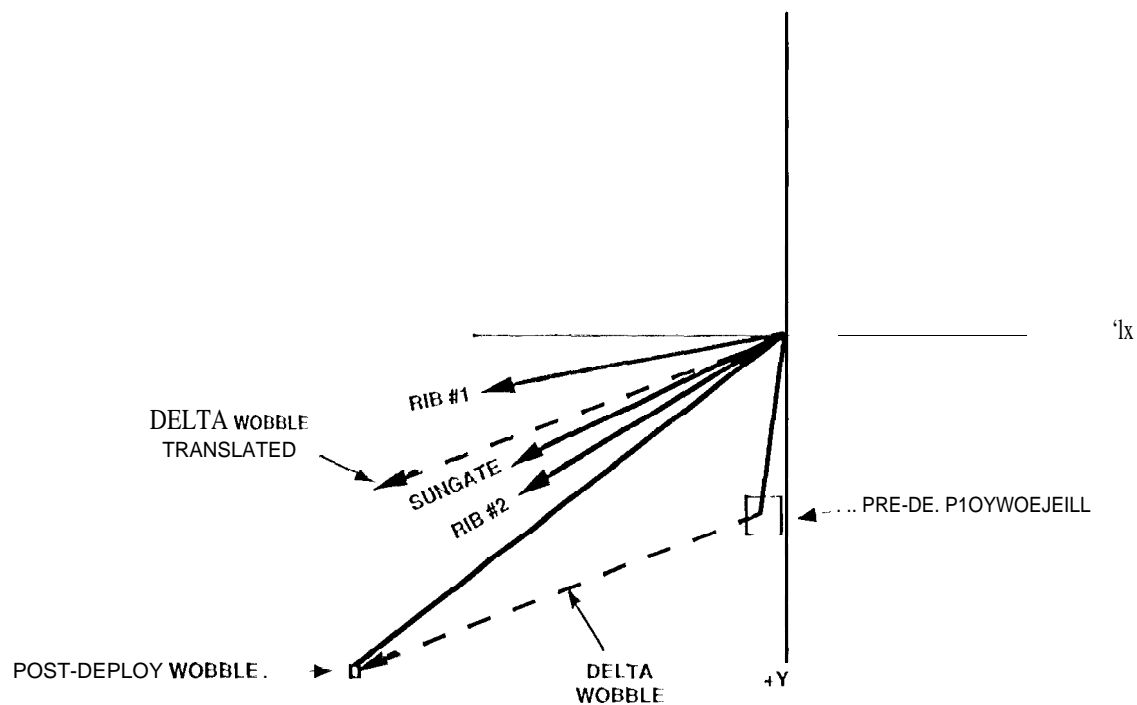


Fig. 8 Spacecraft Wobble Shift

Initially it was thought that the HGA deployed symmetrically for at least a part of the time before stall and that all ribs were free of the tower. There was conjecture that incipient galling in the ball screw had caused the stall. However, analysis of motors-current telemetry indicated that the ball screw completed 5.1 turns before stall (full deployment requires 26 turns). Without the GN&C data there would have been no clue the HGA was asymmetrically deployed. The GN&C data, in conjunction with the motors current data, led to the conclusion that several ribs opposite Rib #2 are very likely stuck to the tower.

Ground tests of the flight-identical spare HGA at JPL, in the summer of 1991 essentially matched the flight signatures. Tying three or four adjacent ribs to the tower resulted in stall in just less than one minute at just over 5 ballscrew turns with the opposite rib deployed 35 deg. The "stuck" rib pushrods hold that side of the deployment carrier ring down, causing the carrier ring to tilt as the carrier hub (ball nut) rises on the turning ballscrew. The large bending moment thereby applied to the ball screw acts as a torque brake, which eventually stalls the drive motors.

It was also concluded that the most likely reason the ribs would be stuck to the tower was loss of the lubrication on the locating pins (Fig. 6) causing the pins to "stick" in their receptacles (see Ref. 7 for details). Eventually, detailed analytical modeling suggested it might be possible to "walk" the pins out of their receptacles by pumping the tower up and down by thermal expansion and contraction, since the graphite epoxy ribs have a negligible coefficient of thermal expansion compared to the tower. The very first theory had suggested that just expanding the tower might free the pins; the next theory proposed that only contraction would work. In all cases, major spacecraft turns off sunline were implemented. Fig. 9 shows that five warming turns and seven cooling turns were performed. Warming turns were 45 deg off sunline; cooling turns 165 deg off sunline.

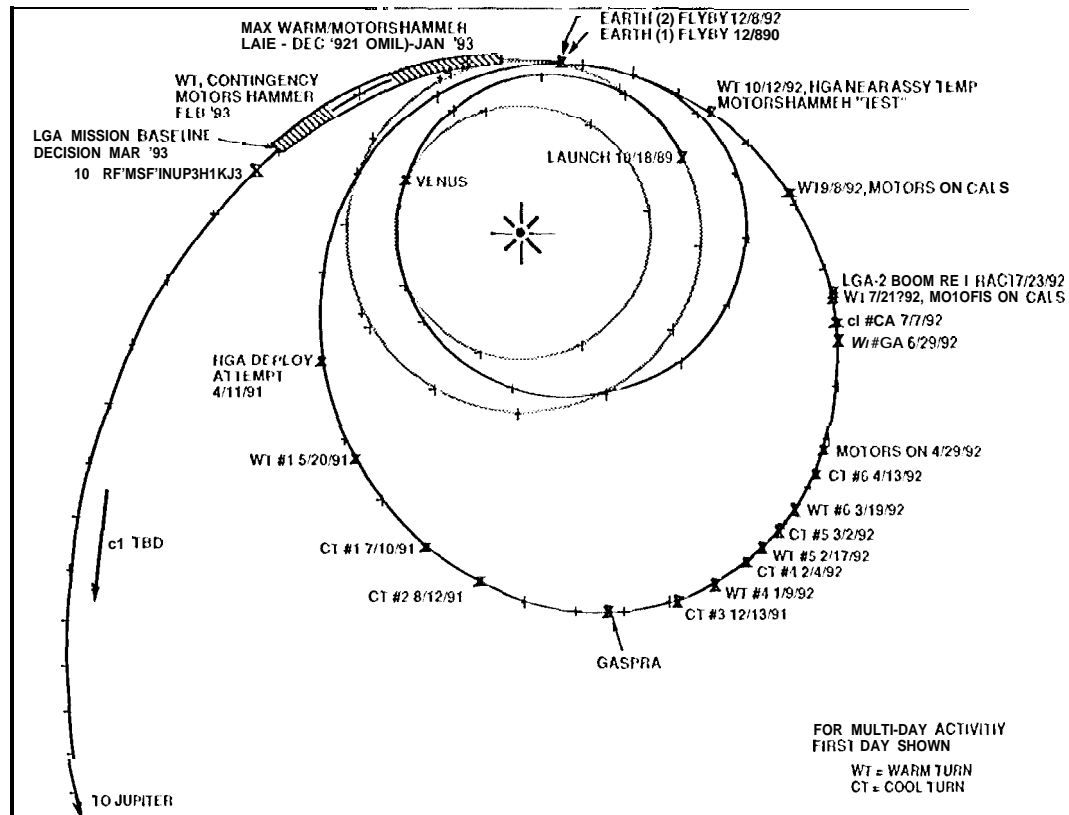


Fig. 9 Galileo 1 IGA Events

The warming and cooling turns were performed using the SITURN (spacecraft inertial turn) "activity". The spacecraft is placed in the dual-spin mode so the gyros on the despun ("stator") side can be used to "track" the re-orientation of the spacecraft spin axis (the centerline or "rotor" axis). The spun side (rotor) roll position is tracked through ICD encoders between the spun and despun sections. The attitude control computer pulses the 1st-thrusters (Fig. 5) once each spacecraft revolution to apply a torque couple that turns the spacecraft angular momentum vector about one degree toward the new desired spin axis direction in space. The momentum vector is thus stepped essentially along a great circle to the desired direction with the spacecraft spin axis precessing in small cones (~1 deg) about each instantaneous momentum vector. The desired direction is commanded as the J2000 right ascension and declination of the spacecraft +Z axis. Following each warming or cooling activity the spacecraft was returned to "sunpoint" by commanding a standard sun acquisition. In sun acquisition the 1st-thrusters are pulsed an exactly prescribed fraction of the spin period after each "sun pulse" seen by the sun-acquisition sensor. This steps the momentum vector and spin axis back to sunpoint along a great circle. Sun acquisition is terminated when the angle between spacecraft -Z and the sunline is reduced to a small prescribed value of typically a few degrees.

During the first two years of flight, sun acquisitions were done to within about a degree of sunline. When planning the 1 December 1991 cooling turn it was determined that "sun stars" were not available; i.e., when the spacecraft pointed within a degree of sunline, an adequate set of three stars would not be available within the star scanner's field of view. Good stars are required for celestial attitude reference, which is prerequisite to turning the

spacecraft. It would be necessary to wait, over a month until the trajectory rotated the sunline to a "sun stars"-available orientation and then a sun acquisition would enable re-establishing celestial reference with stars. This problem was avoided by selecting the spacecraft off-sun turn great circle and sun acquisition threshold angles of 5 to 7 degrees such that stars would be available at the sun acquisition termination attitude.

For each warming and cooling turn, the first indication of a rib release would be a change in the sun gate obscuration following sun acquisition. A rib release would reduce the force holding down the one side of the carrier ring thereby reducing its tilt and Rib #2 would be drawn inboard a few degrees. q'bus, the sun gate data was always awaited with anticipation and viewed with disappointment. Eventually it became apparent there was little reasonable chance that thermal cycling of the HGA would free the ribs. The cycling campaign was abandoned after the seventh cycle in July 1992. Each cycle required a large effort by the Flight Team in spacecraft thermal, power, fault protection, and communications management as well as GN&C. Each cycle consumed 6 kg of propellant, reducing the end-of-mission propellant margin (PM) by 4 kg, and placed another undesirable thermal cycle on some critical electronics.

Stuck pins remain the leading suspect but other mechanisms cannot be ruled out. Early in 1992 tinting of the flight spare HGA showed that the ballscrew could probably be rotated another 1.5 turns past the present stall position by pulsing the motors on and off (Ref. 1) about one thousand times. This would double the force in the most loaded pushrod and perhaps overpower whatever was restraining that rib. Pulsing the motors is called "hammering" the ballscrew. If one rib could be freed, continued hammering was an excellent prospect to free the remaining stuck ribs because even higher pushrod forces would be developed with fewer stuck ribs. Increasing the temperature of the deployment mechanism would increase the hammering torque primarily by reducing the viscosity in the gear train lubricant.

Additionally it was important to expand the HGA central tower to the maximum possible length before increasing the deployment forces. Because Galileo was 1.3 au. from the sun at the deployment attempt, and farther ever since, the tower has been shorter (colder) than at assembly, even during warm turns. It was suggested that perhaps the ribs would release simply by restoring the tower to assembly length.

The ideal time for hammering the ballscrew would be after Earth 2 encounter and shortly after perihelion, namely, in early January 1993 at 1.0 a.u. solar distance. Warming turns would be required to extend the tower and warm the deployment mechanism. Once again there was a great irony-- there were no sun stars in January 1993. As described earlier, warming turns and sun acquisitions slightly off-sun could be designed to jockey the spacecraft between "stars-available" attitudes and sun acquisitions could be inhibited when at the desired attitudes. However, in the event of an attitude anomaly or certain other faults, sun acquisition-- the standard fault protection response would put Galileo in a "no-stars" attitude. Warming turns would then be precluded and the best opportunity for freeing the HGA would be forever lost. To protect against this highly unlikely but unacceptable situation an "open-loop" turn capability was developed. The Command and Data Subsystem (CDS) would be programmed (an uplinked mini-sequence) to pulse the 12 thrusters a prescribed number of times at a prescribed frequency computed on the ground to match the spin period. The pulse count would determine the off-sun angle achieved, typically 30 deg. The Spacecraft inertia ratios (spin/traverse) are such that the momentum vector and precessing spin axis would stay adequately close to a great circle turn. A sun-acquisition would be performed to within one degree of sunline. The opt[]-loop turn would then be initiated and proceed along a

randomly established great circle from sunpoint to the desired off-sun angle (there would be no attempt to time the first pulse to a given roll position because this made the flight/ground interaction much more complex without necessity). After the hammering session, a sun-acquisition would return Galileo to sunpoint. Any number of open-loop warming turns could be performed in this manner. As it turned out, the spacecraft performed all the HGA activities in late December 1992 and January 1993 flawlessly so the open-loop turns were not required. The hammering did advance the ballscrew to 6.4 to 6.6 turns, increasing the deployment forces as planned, but very unfortunately, no ribs were released. Sun gate analysis shows Rib #2 is now -43 deg deployed, which corroborates this ballscrew advance. 'There is no longer any significant prospect of deploying the Galileo HGA. The mission is proceeding with the low-gain antenna mission and at least 70 percent of the science objectives will be satisfied. The entirety of the atmospheric probe mission will be accomplished and thousands of the most stunning Jupiter satellite images ever planned will still be acquired (see Ref. 1).

In closing, there are a few, final GN&C notes. The use of the 10-N thrusters and/or the 400-N main engine to dynamically excite the HGA to release the ribs was exhaustively analyzed in 1991. Because the ribs are very lightweight and the spacecraft is extremely stable and well-controlled, no significant deployment forces can be induced in this manner (Ref. 8). Moreover, while gyrations would break the magnetometer boom; the boom is absolutely essential for spacecraft stability. A "high-spin" of 10 rpm is required for probe release and 400-N engine burns. Analysis shows high spin will reduce deployment force because of the asymmetric state of the HGA. Nonetheless, Galileo will be "spun-up" to 10 rpm on March 11, 1993 to be certain this will not help.

ACKNOWLEDGMENTS

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